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EFFECT OF INJECTOR DESIGN ON EXTERNAL BURNING OF SOLID PROPELLA--ETC(U)
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CHINA LAKE, CALIFORNIA

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Effect of Injector Design on External Burning of Solid Propellants in Mach 2 Airstream

by
Klaus C. Schadow
and
Don J. Chieze
Research Department

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(U) Injector concepts and propellant formulations were evaluated under simulated external burning conditions in a planar, two-dimensional wind tunnel. The ratio of base pressure rise to propellant mass flow was significantly improved by: (1) reduction of the injection velocity from supersonic to subsonic speed, (2) the use of a downstream-facing step upstream of the supersonic and subsonic injector, and (3) the use of magnesium loaded propellants.

CONTENTS

A

INTRODUCTION

The base pressure of a projectile or a missile can be controlled by burning a fuel near the base region. By this means, the base pressure can be raised closer to static free-stream pressure (to reduce base drag), or may be increased above free-stream pressure (to provide thrust). Theoretical calculations[1] suggest that for a propulsion mode, base pressure alteration should be achieved by burning the fuel in the supersonic airstream outside the subsonic base region. Such an external burning propulsion concept is schematically shown in Figure 1a.

It can be seen that fuel-rich reaction products from a solid propellant are injected into the supersonic inviscid flow region outside the projectile boundary and base region. The resulting supersonic combustion creates compression waves which impinge on the projectile base. The achievable base pressure rise (base pressure difference with and without external burning) mainly depends on both the injector concept and the propellant formulation. The effect of both parameters was studied using a two-dimensional (2D) planar wind tunnel. Test results will be reported in this report.

The different injector concepts which were selected for the study are summarized in Figure 1. Figure 1a, a concept commonly used in the past, shows the basic cone-cylinder design of the projectile with fuel injection occurring at 90 degrees (or perpendicular) into the airstream. In Figure 1b fuel injection occurs at less than 90 degrees, so that momentum of the supersonic jet provides a thrust component in addition to the base pressure rise. In Figure 1c the injector velocity is reduced from supersonic to subsonic. In this injector concept the solid propellant reaction products pass through the choked nozzle of the solid propellant chamber and enter the injection channel where reduction to subsonic speed occurs. With subsonic injection, propulsion is achieved by base pressure rise only because of the negligible jet momentum. Reduction of the injection velocity to subsonic speed significantly improved the ignition and combustion characteristics of fuel-rich plumes in a confined, subsonic airstream.[2]

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[1]W. C. Strahle. "Theoretical Consideration of Combustion Effects on Base Pressure in Supersonic Flight," *Twelfth Symposium on Combustion*, The Combustion Institute. Pittsburgh, Pa., 1969, pp. 1163-1173.

[2]K. Schadow. "Fuel-Rich Particle-Laden Plume Combustion," *AIAA Journal*, Vol. 13, No. 12, December 1975, pp. 1553-1554.

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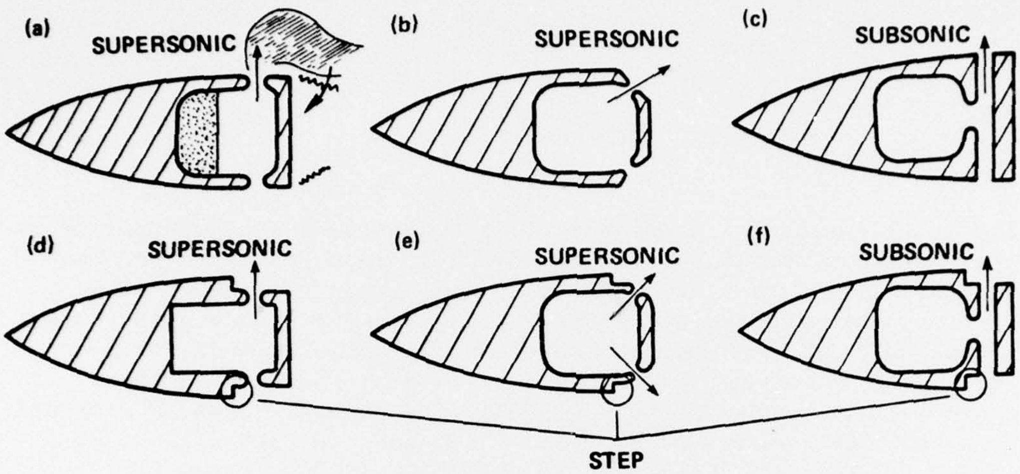

FIGURE 1. Injector Schemes for External Burning Assisted Projectiles. Basic cone-cylinder design in Figures 1a to 1c; modified design with down stream facing step in Figures 1d to 1f.

In Figures 1d to 1f the basic cone-cylinder design is modified with a downstream facing step upstream of the supersonic (Figure 1d and 1e) and subsonic (Figure 1f) injector. It was anticipated that the step may act as a flameholder for the plume ignition process.

Two solid propellant formulations were studied: (1) 80% by weight ammonium perchlorate (AP)/20% hydroxyl terminated polybutadiene (HTPB), and (2) 20% magnesium (Mg)/60% AP/20% HTPB.

For the parametric study the external burning environment was simulated in a planar, 2D wind tunnel by burning one single fuel-rich plume in a supersonic airstream. The performance of the injector concepts and propellant formulations was evaluated and graded on the basis of the ratio of base pressure rise to propellant mass flow. The 2D wind tunnel was chosen as a low cost method to screen and select injector designs and propellant formulations for further evaluation in more expensive free-flight and/or wind tunnel tests with large scale axisymmetric models. These tests will be necessary to make final conclusions on performance on the basis of measured specific impulse.

In addition, for screening purposes, the 2D wind tunnel was expected to be a good tool to study the external burning processes and to explain

the performance differences which were expected for the various injector concepts and propellant formulations. The results of these diagnostic studies will be published in a later report.

TEST SETUP

The planar, 2D wind tunnel for combustion studies of one fuel-rich jet in a supersonic airstream is shown in Figure 2. The air entered the test section, which has a width of 1.5 inches (38.1 mm), from the left and expanded to a Mach 2 airstream of 11.3 psia (78.0 kPa) free-stream pressure and ambient temperature, simulating an altitude of 6700 feet (2000 m). The free-stream pressure was determined through four orifices in one of the tunnel walls. The position of the orifices may be seen from Figure 2. Near the right end of the test section the sudden expansion of the flow area with a step height of 1.75 inch (44.5 mm) caused air flow separation and the formation of a separation bubble. This separation region simulated the subsonic base region downstream of a projectile base. With only air flowing through the test section, a base pressure of 7.9 psia (54.5 kPa) minimum was recorded. The base pressure was measured at four different locations (p_{B1} to p_{B4}) as shown in Figure 2. The four base pressures deviated by ±0.2 psi (1.38 kPa). In this report, only the base pressure p_{B1} will be discussed.

The primary motor with fuel-rich propellants (80 AP/20 HTPB and 20 Mg/60 AP/20 HTPB) was attached on the bottom of the wind tunnel. Internally burning tubular grains were used which provided a propellant mass flow ($\dot{m}_{pr}$) increase by a factor of three. The mass flow increase resulted in a pressure increase from 100-300 psi (690-2.1 x 10^3 kPa) during burning. Further mass flow variation was achieved by varying the grain tube length from test to test. During the entire test program $\dot{m}_{pr}$ was varied between 0.020 and 0.177 lb/s (0.009 and 0.057 kg/s). For grains with different tube lengths, different motor throats were used to keep the chamber pressure variation in the 100-300 psia range.

The fuel-rich exhaust products were injected into the airstream through the injector, $D_{T,INJ}$. To simulate the different injector schemes discussed in Figure 1, the plate holding the injector and the connection to the primary motor was changed. The injector plate in Figure 2 simulates the injector concept in Figure 1d with supersonic injection and the modified projectile design with a downstream facing step. For supersonic injection, $D_{T,INJ}$ was smaller than D_{TM}. For subsonic injection $D_{T,INJ}$ was larger than D_{TM}. The detailed injector geometries will be discussed later in the context of Table 1.

The effect of external burning was determined by measuring the base pressure difference with and without burning (base pressure rise).

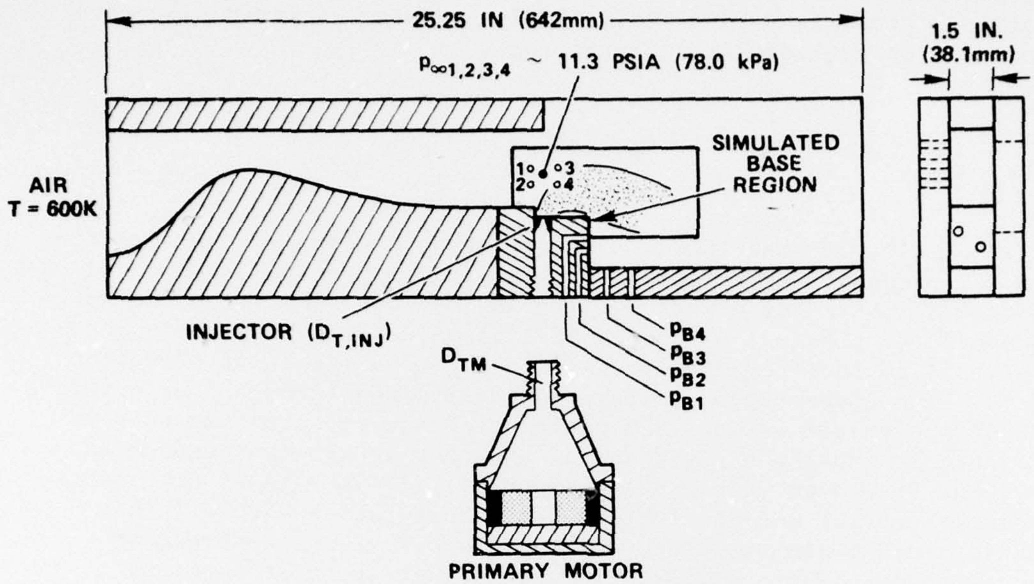

FIGURE 2. Two-Dimensional Planar Wind Tunnel for Simulating External Burning at Flight Conditions at Mach 2, 6700 Feet (2000 m) Altitude.

The flame characteristics were recorded through a quartz window on color film; however, the results of the color movies will be discussed in a later report.

TEST MATRIX

A total of 15 tests were made to evaluate six injector concepts (described in Figure 1) and two propellant formulations. The test parameters are shown in Table 1. This table is horizontally divided into six groups, which correspond to the six injector concepts. With each concept, tests were made with the AP/HTPB and AP/HTPB/Mg propellants. Tests 1 through 9 were made to simulate the basic cone-cylinder projectile design (no step). Tests 10 through 15 were made with the modified design with downstream facing step. The step height, H_S, varied between 0.375- and 0.6-inch (9.5 and 15.2 mm) as shown in the Table.

TABLE 1. Test Data and Results.

Test No.	Propellant	Injector profile (Figure No.)	Step height, H_S		Injector throat, $D_{T,INJ}$		Motor throat, $D_{T,M}$		Base pressure: Air-only, $p_{B1,air}$		Base pressure: External burning, p_{B1}		$\dot{m}_{pr}$		Motor pressure, p_c		Base pressure rise ratio, $\Delta p/\dot{m}_{pr}$, $\frac{psia \cdot sec}{lb}$	Remarks
			in.	mm	in.	mm	in.	mm	psia	kPa	psia	kPa	lb/s	kg/s	psia	kPa		
1	AP/HTPB[a]	1a	--	--	0.2	5.1	--	--	8.0	55.2	6.9	47.6	0.077	0.035	344	2.4×10^3	0	No ignition
2a	Mg[b]	1a	--	--	0.2	5.1	--	--	8.0	55.2	8.2	56.6	0.021	0.009	96	0.6×10^3	25	
2b	Mg[b]	1a	--	--	0.2	5.1	--	--	8.0	55.2	10.0	69.0	0.077	0.035	344	2.4×10^3	25	
3	AP/HTPB	1b, 60 deg	--	--	0.27	6.9	--	--	8.0	55.2	6.3	43.5	0.725	0.052	261	1.8×10^3	0	No ignition
4	AP/HTPB	1b, 45 deg	--	--	0.25	6.4	--	--	7.7	53.1	7.1	49.0	0.090	0.041	237	1.6×10^3	0	No ignition
5	Mg	1b, 60 deg	--	--	0.27	6.9	--	--	8.3	57.3	10.9	75.2	0.046	0.021	114	0.8×10^3	60	
6	Mg	1b, 45 deg	--	--	0.14	3.6	--	--	8.3	57.3	11.4	78.7	0.032	0.014	297	2.4×10^3	100	
7	Mg	1b, 30 deg	--	--	0.14	3.6	--	--	8.0	55.2	11.7	80.7	0.024	0.011	216	1.5×10^3	150	
8	AP/HTPB	1c	--	--	0.4	10.2	0.2	5.1	7.9	54.5	6.3	43.5	0.127	0.057	--	--	0	No ignition
9	Mg	1c	--	--	0.4	10.2	0.14	3.6	7.9	54.5	12.8	88.3	0.020	0.009	184	1.4×10^3	250	
10a	AP/HTPB	1d	0.375	9.5	0.2	5.1	--	--	9.6	66.2	6.9	47.6	0.066	0.030	276	1.9×10^3	0	No ignition
10b	AP/HTPB	1d	0.375	9.5	0.2	5.1	--	--	9.6	66.2	11.0	75.9	0.119	0.054	498	3.4×10^3	25[c]	
11	Mg	1d	0.5	12.7	0.14	3.6	--	--	10.2	70.4	11.3	78.0	0.035	0.016	317	2.2×10^3	100[c]	
12	AP/HTPB	1e, 60 deg	0.5	12.7	0.27	6.9	--	--	8.4	58.0	10.5	72.5	0.059	0.027	133	0.9×10^3	50[c]	
13	AP/HTPB	1e, 45 deg	0.6	15.2	0.25	6.4	--	--	8.6	59.3	8.2	56.6	0.092	0.041	243	1.7×10^3	0	No ignition
14	AP/HTPB	1f	0.375	9.5	0.4	10.2	0.2	5.1	9.7	66.9	10.5	72.5	0.054	0.024	224	1.5×10^3	50[c]	
15	Mg	1f	0.5	12.7	0.4	10.2	0.2	5.1	9.8	67.6	12.0	82.8	0.020	0.009	89	0.6×10^3	200[c]	

[a] 80 AP/20 HTPB.

[b] 60 AP/20 HTPB/20 Mg.

[c] Includes effect of boattailing (Δp based on $p_{B1,air}$ = 8.0 psia).

In the tests with supersonic injection (Tests 1 through 7 and 10 through 13), the injector throat, $D_{T,INJ}$, varied between 0.14- and 0.2-inch (3.6 and 5.1 mm) to keep p_c in the 100-300 psia (6.9-20.7 x 10^3 kPa) range in the tests with various grain lengths. In the test with subsonic injection (Tests 8, 9, 14, and 15), $D_{T,INJ}$ was held constant at 0.4-inch (10.2 mm). The motor throat for subsonic injection, $D_{T,M}$, varied between 0.14 and 0.2 inch (3.6 and 5.1 mm)

During each test the following measurements were made (see Table 1): (1) base pressure with only air flowing through the wind tunnel, $p_{B1,air}$, (2) base pressure with external burning, p_{B1}, (3) propellant mass flow, $\dot{m}_{pr}$, at the time of p_{B1}-measurement, and (4) motor chamber pressure, p_c. For each test the ratio of base pressure rise (Δp) to propellant mass flow ($\dot{m}_{pr}$) was calculated. The pressure rise, Δp, is the base pressure difference with and without external burning ($\Delta p = p_{B1} - p_{B1,air}$).

TEST RESULTS AND DISCUSSION

The evaluation of the injector concepts and propellant formulations under simulated external conditions is based on (1) base pressure with air flow only, $p_{B1,air}$, (2) base pressure with external burning, p_{B1}, and (3) the ratio of base pressure rise to propellant mass flow ($\Delta p/\dot{m}_{pr}$).

BASE PRESSURE WITH AIR FLOW ONLY

This pressure, $p_{B1,air}$, was determined to be 8.0 ± 0.3 psia (55.2 ± 2.1 kPa) for the injector concepts in Figures 1a, b, and c for the basic cone-cylinder design (Tests 1 through 9). For the modified design with step in Figures 1d, e, and f (Tests 10 through 15), $p_{B1,air}$ was generally higher (8.4-10.2 psia [58.0-70.4 kPa]). The higher base pressure with the modified design indicated that the step acted like a projectile boattail which can effectively increase the base pressure by manipulation of the expansion flow around the base corner.[3]

Despite the higher $p_{B1,air}$ for the profiles simulating the modified design with step, the calculation of the base pressure rise, Δp, for these profiles was based on $p_{B1,air}$ = 8.0 psia (55.2 kPa), the base pressure for the profiles without step. This was done, because it is *impossible*, at the present time, to separate the base pressure rise for the modified design into pressure rise components due to boattailing and external burning.

[3]H. H. Kurweg. "Interrelationship Between Boundary Layer and Base Pressure," *Journal Aeronautical Science*, Vol. 18, 1951, pp. 743-748.

BASE PRESSURE DURING EXTERNAL BURNING

The base pressure during external burning, p_{B1}, for the six injector concepts and both of the propellant formulations is shown in Figure 3.

With AP/HTPB (no Mg) external burning was not achieved with the basic cone-cylinder projectile design. The base pressure even decreased during injection from $p_{B1,air}$ = 8.0 psia (55.2 kPa) with air flow only to about p_{B1} = 7 psia (48.3 kPa) (Tests 1, 3, 4, and 8). To explain this base pressure decrease during the injection of hot, non-burning gases, further detailed information on the interaction between the injection process and the air flow expansion process around the base corner is necessary.

With the same propellant (AP/HTPB), however with the modified design with step, external burning was achieved and the base pressure increased to 11 psia (75.9 kPa) for $\dot{m}_{pr} \geqq$ 0.119 lb/s (0.054 kg/s) and supersonic injection at a 90-degree angle (Test 10b). At 60 degrees (Test 12) p_{B1} was slightly lower (10.5 psia [72.5 kPa]). Despite the lower base pressure at 60 degrees injection, this concept may give higher specific performance because at fuel injection at less than 90-degree angles, propulsion is achieved by the momentum of the supersonic exhaust in addition to the base pressure rise. In these tests with the non-metallized propellants the base pressure never exceeded the free-stream pressure upstream of the injector (p_∞ = 11.3 psia [78.0 kPa]).

With the Mg-propellants external burning was achieved with all of the six injector concepts and the base pressure was generally higher than with non-metallized propellants. The highest base pressure was achieved with subsonic injection and the basic cone-cylinder design (12.8 psia [88.3 kPa] in Test 9). The base pressure was slightly lower with the modified design with step (12.0 psia [82.8 kPa] in Test 15). With supersonic injection the base pressure was highest at 30 degrees (11.7 psia [80.7 kPa] in Test 7), and decreased to 10 psia (6.9 kPa) at 90 degrees (Test 2b). The base pressures in the tests with subsonic injection and supersonic injection at 30 degrees are higher than the air free-stream pressure (p_∞ = 11.3 psi [78.0 kPa]).

RATIO OF BASE PRESSURE RISE TO PROPELLANT MASS FLOW ($\Delta p/\dot{m}_{pr}$)

The comparison of the injector concepts on the basis of $\Delta p/\dot{m}_{pr}$ in Figure 4 will provide qualitative information on the specific performance (specific impulse) of the injectors. To achieve highest specific performance, $\Delta p/\dot{m}_{pr}$ should be as high as possible (high Δp at low $\dot{m}_{pr}$).

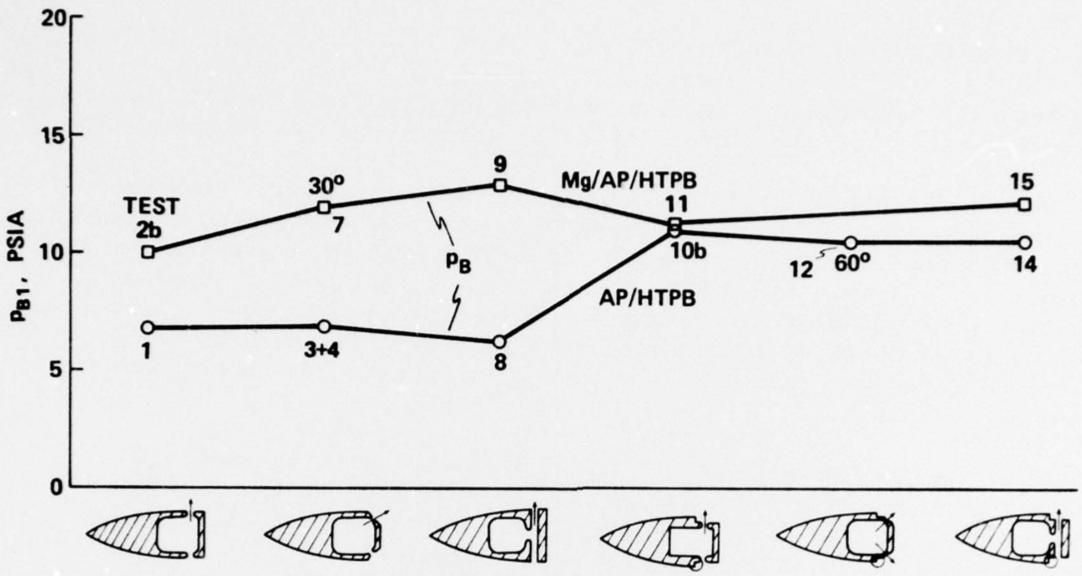

FIGURE 3. Base Pressure During External Burning.

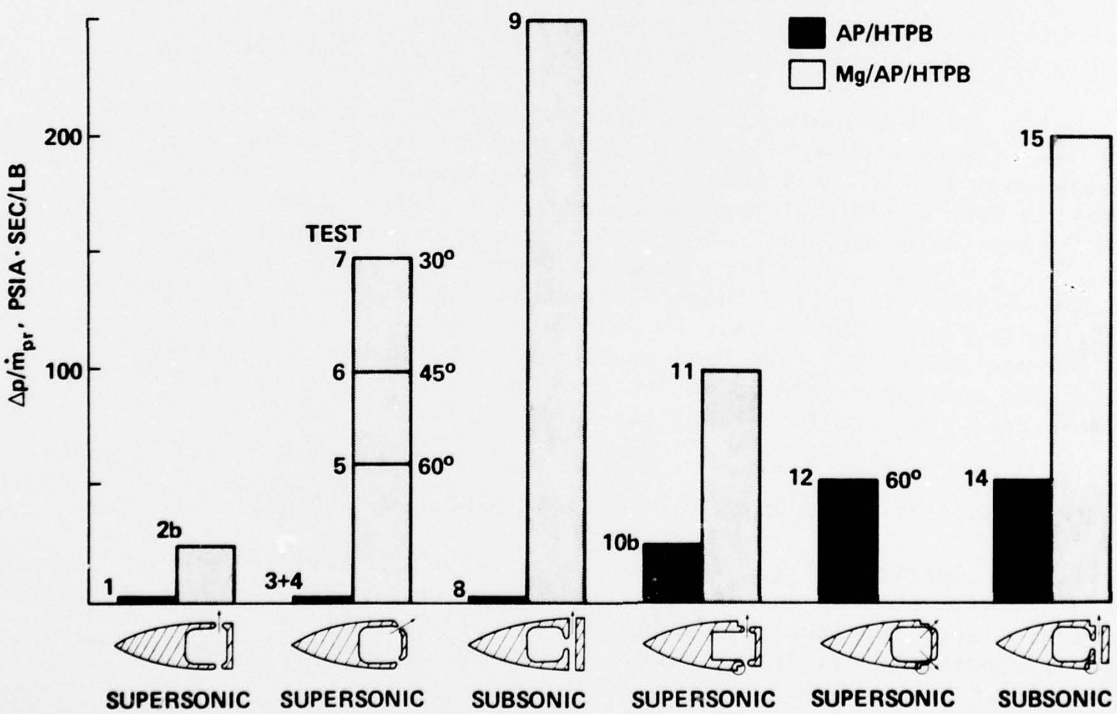

FIGURE 4. Ratio of Base Pressure Rise to Propellant Mass Flow.

With the non-metallized AP/HTPB propellants, no base pressure rise was achieved with the basic cone-cylinder design. With the same propellants and the modified design with step, $\Delta p/\dot{m}_{pr}$-ratios of 50 psia · s/lb were achieved with supersonic injection at 60-degree angles (Test 12) and subsonic injection (Test 14).

The $\Delta p/\dot{m}_{pr}$-ratios were significantly higher with the Mg-propellants. The highest $\Delta p/\dot{m}_{pr}$-ratios were achieved with subsonic injection and the basic cone-cylinder design ($\Delta p/\dot{m}_{pr}$ = 250 in Test 9) and the modified design with step ($\Delta p/\dot{m}_{pr}$ = 200 in Test 15). With supersonic injection, $\Delta p/\dot{m}_{pr}$ was lower than with subsonic injection. The $\Delta p/\dot{m}_{pr}$-ratio was 150 at 30-degree injection angle (Test 7) and decreased with increasing injection angle to 100 (45 degrees in Test 6), 60 (60 degrees in Test 5), and 25 (90 degrees in Test 2b).

CONCLUSIONS

Six injector designs and two propellant formulations were evaluated under simulated external burning conditions. The following conclusions can be made:

1. The ratio of base pressure rise to propellant mass flow ($\Delta p/\dot{m}_{pr}$) was significantly higher with Mg/AP/HTPB than with AP/HTPB.

2. The ratio $\Delta p/\dot{m}_{pr}$ was lowest in the tests simulating the basic cone-cylinder projectile design with supersonic fuel injection under 90 degrees ($\Delta p/\dot{m}_{pr}$ =25). This concept was commonly used in the past.

3. With the basic cone-cylinder design and supersonic injection, $\Delta p/\dot{m}_{pr}$ increased by a factor of six when the injection angle was decreased from 90 degrees ($\Delta p/\dot{m}_{pr}$ = 25) to 30 degrees ($\Delta p/\dot{m}_{pr}$ = 150).

4. With the basic cone-cylinder design, maximum $\Delta p/\dot{m}_{pr}$ (250) was achieved by reduction of the injection velocity from supersonic to subsonic speed. With subsonic injection, $\Delta p/\dot{m}_{pr}$ was increased by a factor of ten compared to the commonly used supersonic injection at 90 degrees.

5. Modification of the basic cone-cylinder design with a step upstream of the injector did not further increase $\Delta p/\dot{m}_{pr}$ in tests with subsonic fuel injection. With supersonic fuel injection at 90-degree the modification with the step increased $\Delta p/\dot{m}_{pr}$ by a factor of four (25 to 100).

Conclusions 3 to 5 were made for tests with Mg propellants.

FUTURE WORK

Diagnostic studies in the 2D wind tunnel are being performed to identify the processes which provide the demonstrated improvements. Furthermore, wind tunnel tests with axisymmetric models are being prepared to further evaluate the new concepts.